DMR 02-10519 NIRT: Interlayer exchange coupling in GaMnAs/GaAs ferromagnetic semiconductor superlattices with and without charge carriers in non-magnetic layers

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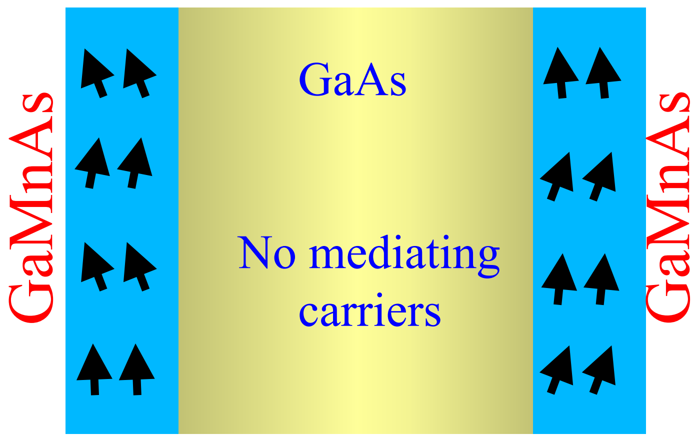
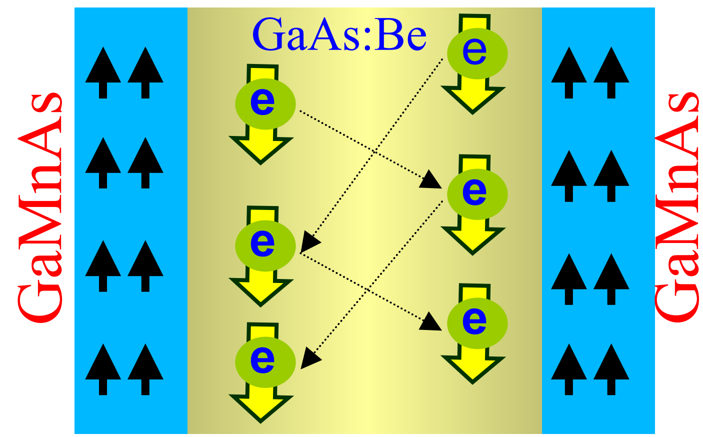
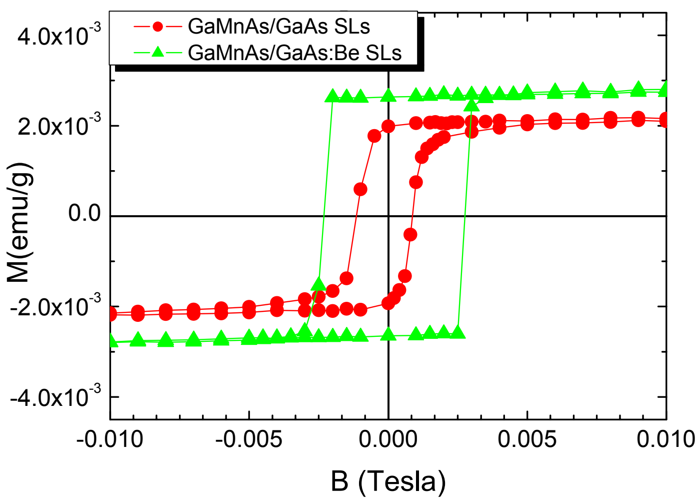
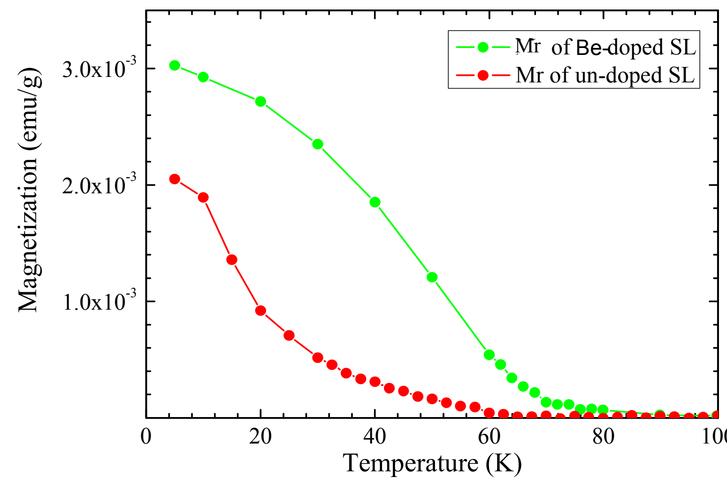








Magnetization curves for Be-doped and undoped GaMnAs/GaAs SLs obtained with an in-plane magnetic field. Much larger coercivity and remanent magnetization Mr is observed in the Be-doped sample. The increased hardness of magnetization and increased Mr in the SL with Be-doped GaAs layers is related to interlayer coupling introduced by doping of the GaAs layers. [S. J. Chung *et al.*, J. Appl. Phys. **95**, 7402(2004)]

Additional comments & observations:

The accuracy and reliability of manipulating and controlling the spin (magnetic) degrees of freedom in novel electronic devices is a key ingredient for making semiconductor-based quantum computation and/or spin electronics (“spintronics”) a reality. Recently, magnetic semiconductors (in which both charge and spin degrees of freedom can be utilized) have become leading candidates for this purpose. Since future spintronic devices are expected to be in the form of composite heterostructures, controlling magnetic properties of multilayers is of special importance. But when the magnetic system is in multilayer form, there is the added phenomenon of inter-layer exchange coupling (IEC) between magnetic layers, which changes the magnetic properties of such multilayer systems and must therefore be understood.

Since magnetic interactions in general are mediated by free carriers, in the case of multilayers it is logical to investigate the role of carriers introduced into non-magnetic layers that separate magnetic layers. In the present case we have explored the effect of free carriers on IEC in superlattices (SLs) consisting of alternating magnetic GaMnAs and non-magnetic GaAs layers, by introducing beryllium impurities in GaAs layers to produce free carriers. We have fabricated a series of such SLs with and without Be in the GaAs spacer layers. By comparing the magnetic properties observed in SLs with and without free carriers in the “spacer” GaAs layers, we were able to identify the contribution of free carriers in mediating the IEC between magnetic layers of the system. While the SLs with Be in GaAs (i.e., with free carriers that carry magnetic information from one GaMnAs to another across the “spacer”) exhibited robust (increased magnetic hardness (coercive field), total magnetic moment (larger saturation magnetization), and higher Curie temperature) magnetic properties even at relatively high temperatures, the SL without the mediating carriers showed a fast decrease of magnetization with increasing temperature. It is clear that the observed magnetic robustness in SLs with Be in the GaAs layers is related to the enhancement of inter-layer coupling achieved by introduced free carriers into the nonmagnetic layers. A portion of this work was published in Journal of Applied Physics [S. J. Chung *et al.,* J. Appl. Phys. 95, 7402(2004)].

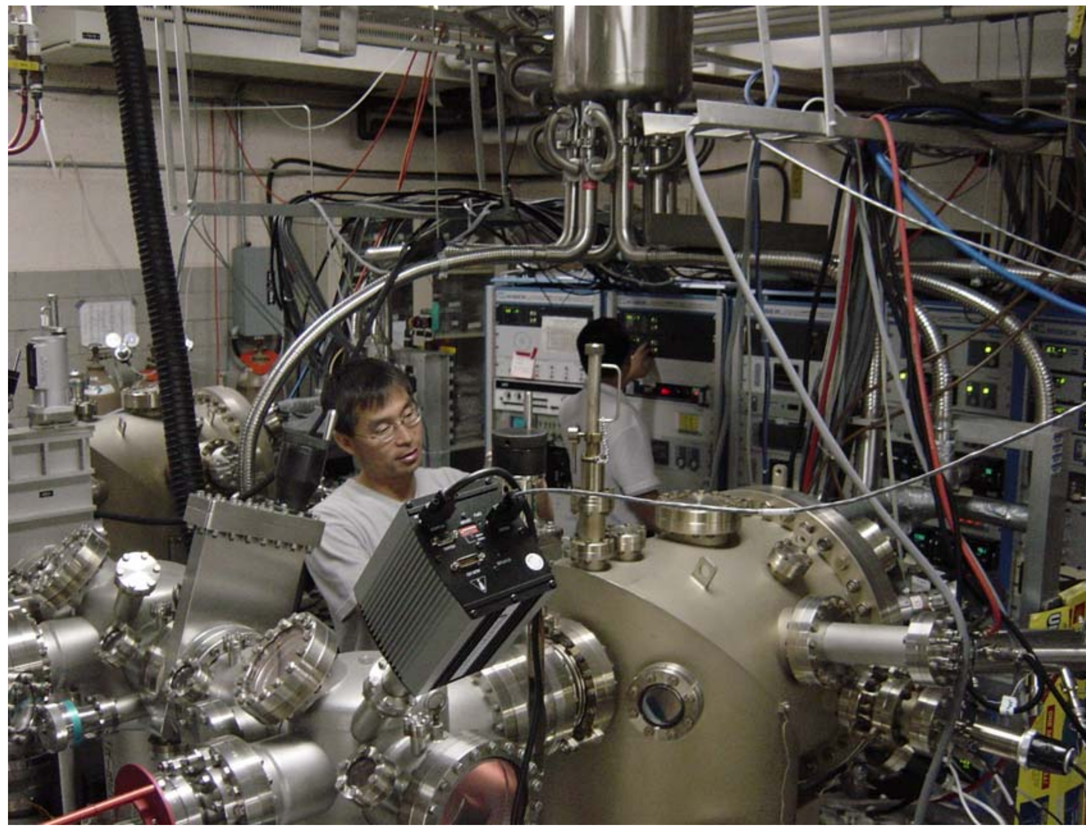
DMR 02-10519 NIRT: Formation and Properties of Spin-Polarized Quantum Dots in Magnetic Semiconductors by Controlled Variation of Magnetic Fields on the Nanoscale

B. Jankó, J. Furdyna, M. Dobrowolska, *Notre Dame*,
V. Metlushko, *Univ. of Illinois, Chicago*, Albert Chang, *Duke*

EDUCATION & OUTREACH

- Visiting Assistant Professor S. Lee (front) and Post-Doctoral Research Associate X. Liu (back) are growing nano-magnetic semiconductor samples by molecular beam epitaxy (MBE).

-International visitor exchange at levels from undergraduate student to associate professor, from six different nations on three different continents. **[see participants and image at http://www.nd.edu/~condmat/]**



DMR 02-10519 NIRT: Magneto-photoluminescence study of the effect of inter-dot coupling on spin polarization of carriers in pairs of quantum dots

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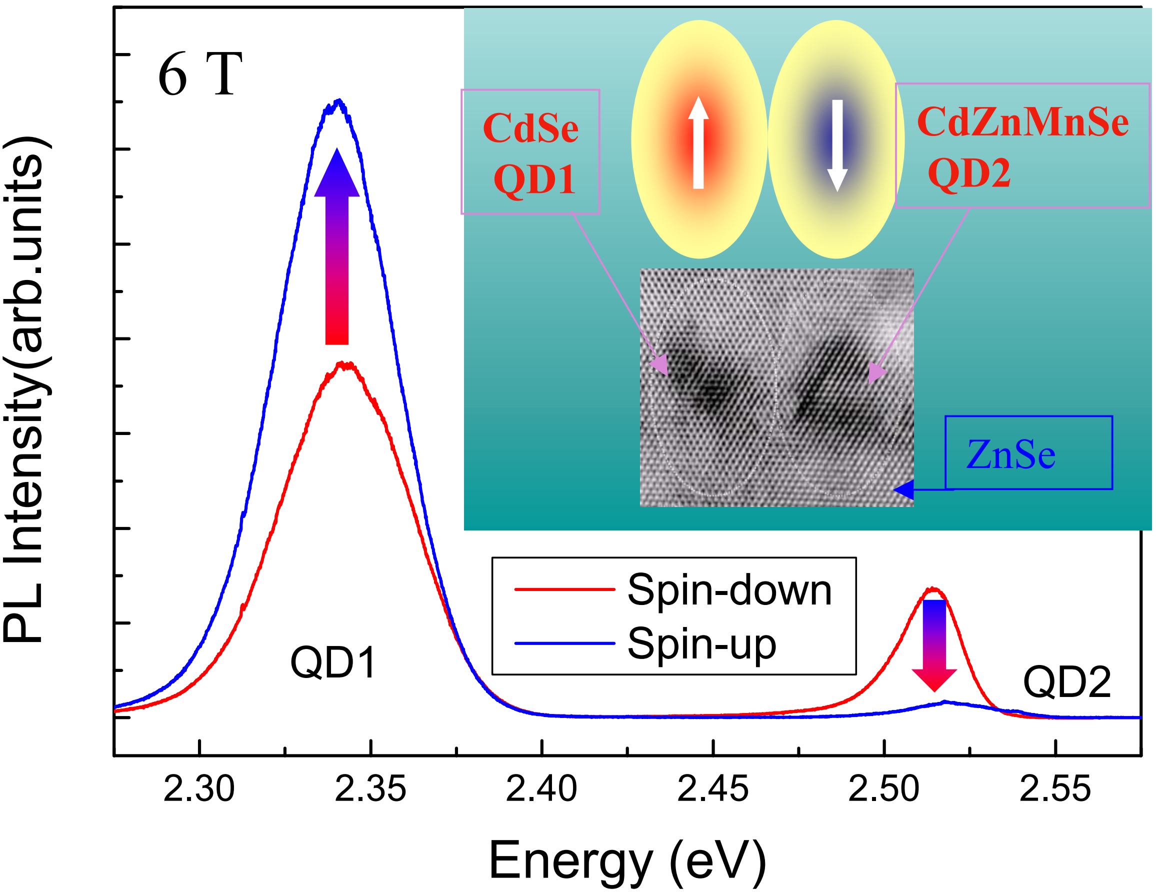

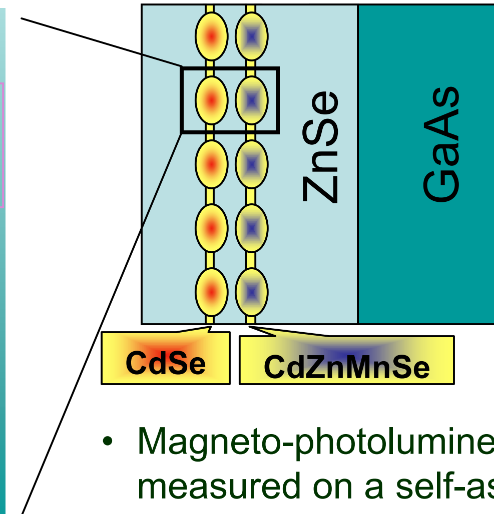

Magneto-PL spectra taken on CdSe and CdZnMnSe double layer QD systems. The red and blue lines are the spectra taken at magnetic field 6.0 T with σ^+ and σ^- circular polarizations, respectively. Note that the peak intensities of the two PL peaks vary in opposite direction in an applied magnetic field. [S. Lee *et al.*, Semicond. Sci. Technol. **19** (2004) 1125–1130]

- Magneto-photoluminescence (PL) is measured on a self-assembled coupled double quantum dot (QD) system consisting of adjacent CdSe QD (QD1) and CdZnMnSe QD (QD2) layers.
- The PL peaks from QD1 and QD2 exhibit significant intensity differences for the two spin states when a magnetic field is applied.
- The observed behavior can be interpreted in terms of anti-ferromagnetic spin-interaction between carriers localized in pairs of QDs that are electronically coupled.

Additional comments & observations:

Coupling between electronic states is a fundamental quantum phenomenon, which appears in many fields of physics. With the development of epitaxial techniques for fabricating zero-dimensional semiconductor quantum dots (QDs) that are characterized by atomic-like energy levels, the interest of the scientific research has automatically turned to inter-dot coupling phenomena – a feature that is becoming increasingly important for the utilization of these nano-structures in multi-QD systems. The coupling between states of semiconductor QD structures leads to many new basic physical phenomena, e.g., the energy shift of coupled QD states, wave function mixing, and resonant tunneling. In addition – since there have been proposed a number of schemes for utilizing QD ensembles in quantum computation – such coupling is of central interest in that applied context. The most informative and simplest QD structure for studying such coupling phenomena is the double QD system.

Here we discuss the phenomenon of spin polarization of carriers that arises from inter-dot coupling between QD pairs which occurs when two layers of QDs are adjacent to one another. To study spin polarization of carriers in such coupled QD structures, we used polarization-selective magneto-photoluminescence (PL). Specifically, we have strategically designed double layer QD structures having different eigen-energies, so as to separate the PL signal from the two QD layers, thus enabling us to study the polarization of the PL from each QD layer separately. Furthermore, we performed these PL experiments with excitation energy below the ZnSe band gap (i.e., 458 nm = 2.707 eV) to eliminate contributions from ZnSe barrier material in which the QDs are embedded. In this situation, the PL intensity is directly proportional to the number of carriers recombining within the dots. Since the polarization of the PL provides information on the spin polarization of the carriers in the dots, its behavior in the presence of a magnetic field reflects variations of how the different spin states of the QDs are populated. By a careful analysis of the polarization dependence of the two PL peaks emitted by the double QD layer, we were able to study the enhancement (or suppression) of spin polarization of carriers arising from the coupling between pairs of QD in the double-layer system.

The PL signal was studied using circularly polarized detection. The intensities of the PL peaks emitted by the interacting QDs from the two QD layers exhibited a strikingly different ehavior for the two circular polarizations when a magnetic field was applied, as shown in the figure. The observed behavior demonstrates that – due to the interaction between carriers localized in pairs of QDs – spins in a given QD force the spins in its neighbor into opposite (i.e., antiferromagnetic) alignment. Thus, by controlling spins in one QD, we now have a handle to control the spins in its neighbor.

A portion of this work was published in Semiconductor Science and Technology [S. Lee *et al.,* Semicond. Sci. Technol. 19 (2004) 1125–1130].

DMR 02-10519 NIRT: Formation and Properties of Spin-Polarized Quantum Dots in Magnetic Semiconductors by Controlled Variation of Magnetic Fields on the Nanoscale

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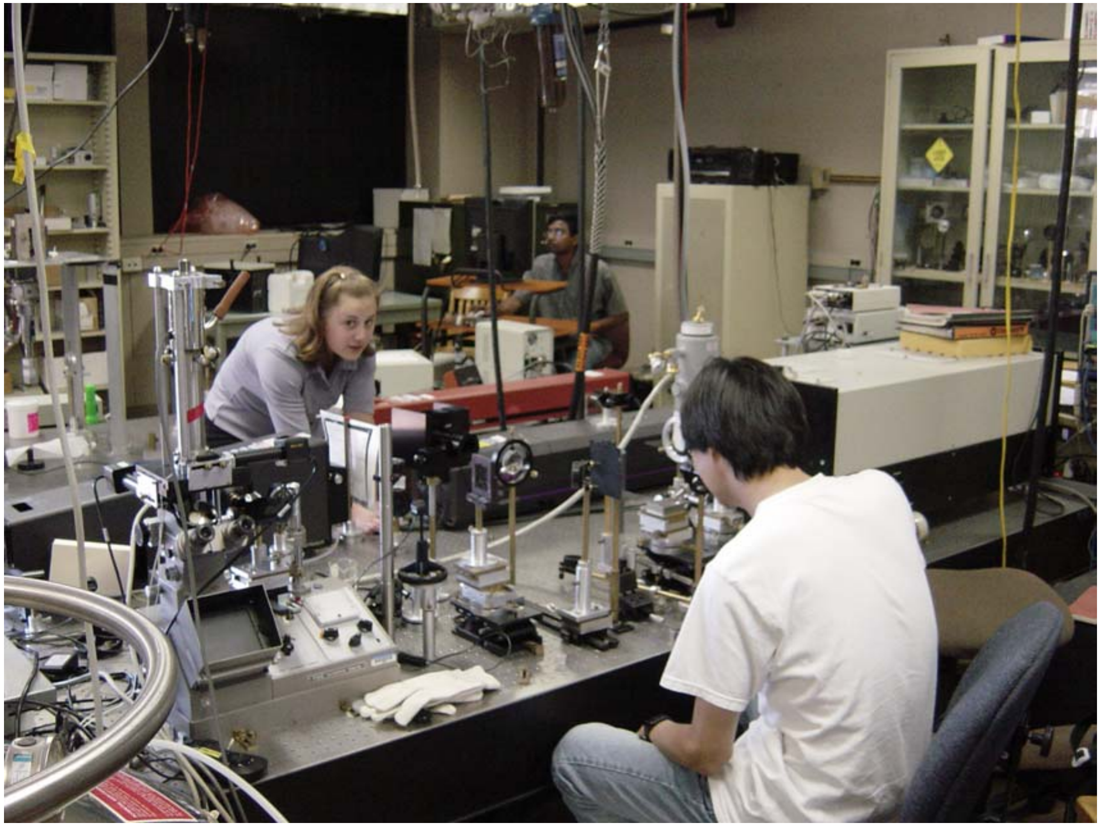
EDUCATION & OUTREACH

- Undergraduate student Patricia Egeler (right) and first-year graduate student Yong-Jin Cho (left) are aligning the Ti-Sapphire tunable laser for micro-PL experiment on nano-magnetic quantum dot samples. Third-year graduate student Raja Chakarvorty (center back) is collecting experimental data.

- International visitor exchange at levels from undergraduate student to associate professor, from six different nations on three different continents.

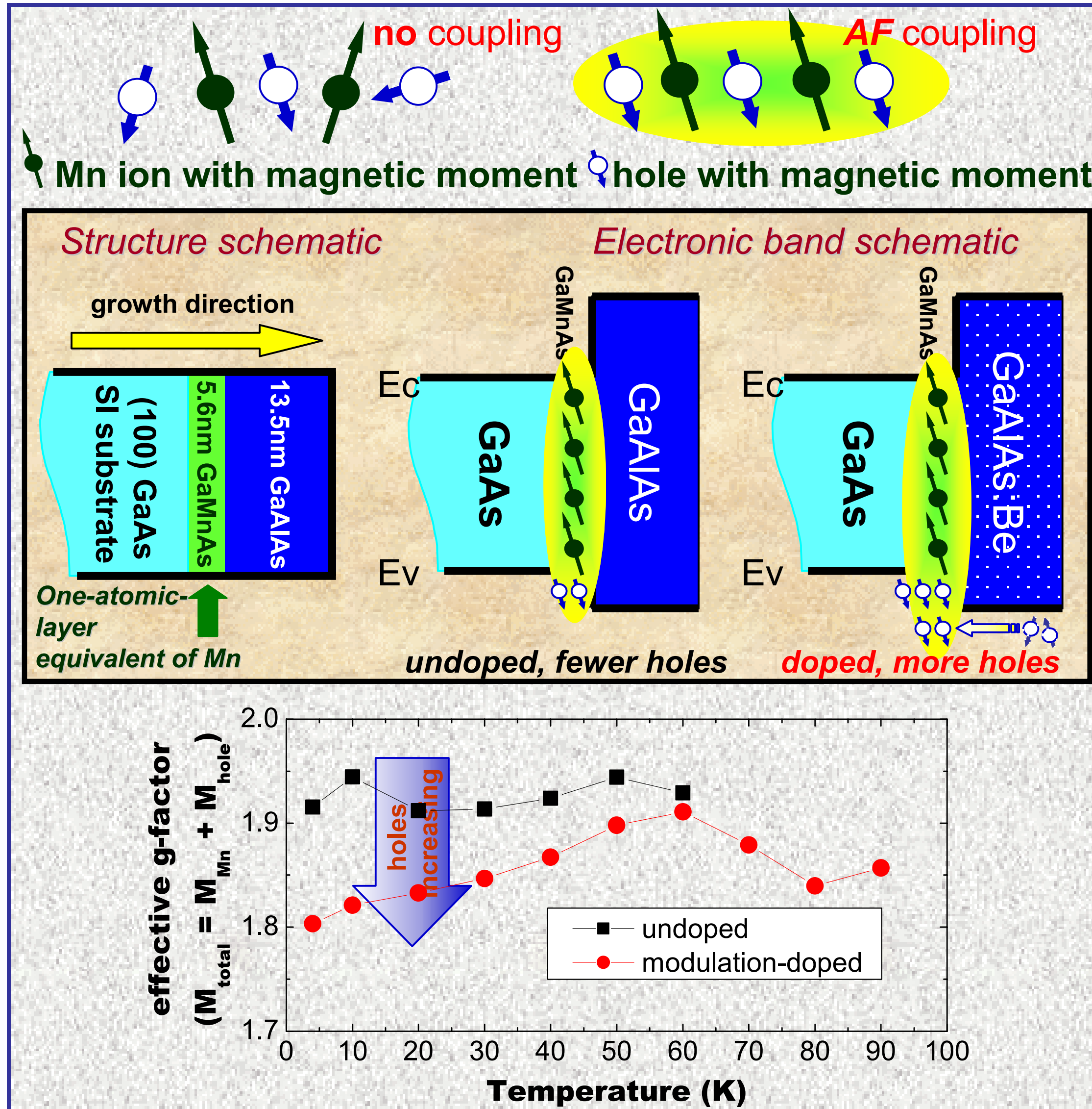
[see participants and image at http://www.nd.edu/~condmat/]



DMR 02-10519 NIRT: Ferromagnetic resonance study of free hole contribution to magnetization and magnetic anisotropy in modulation-doped $Ga_{1-x}Mn_xAs/Ga_{1-y}Al_yAs:Be$

B. Jankó, J. Furdyna, M. Dobrowolska, *Notre Dame*,
V. Metlushko, *Univ. of Illinois, Chicago*, Albert Chang, *Duke*

- Mn ions and free holes in GaMnAs form a complex system via strong anti-ferromagnetic (**AF**) coupling.
- We introduce additional free holes into a 5.6nm GaMnAs layer using modulation doping (**MD**) by beryllium.
- Ferromagnetic resonance experiments show that MD unambiguously affects the effective *g*-factor of GaMnAs – the total magnetic moment of Mn-ion/hole complex decreases as the hole concentration increases.
- [X. Liu *et al.*, cond-mat/0407371]



Additional comments & observations:

Magnetic anisotropy in ferromagnetic (FM) semiconductors such as GaMnAs is expected to play a key role in future spin-based devices utilizing these materials. Although it is now well established that the magnetic anisotropy of III-Mn-V alloys is directly linked to the properties of free carriers mediating the interaction between magnetic Mn ions, the correlation between the magnetic anisotropy and the free carrier concentration is not yet well established.

To address this issue, have we introduced additional free holes into GaMnAs/GaAlAs heterostructures by introducing beryllium (Be) into the GaAlAs barrier layers. The heterostructure is grown on GaAs (100) semi-insulating (SI) substrate. After deposition of 5.6nm (20 monolayer) $Ga_{0.94}Mn_{0.06}As$ magnetic layer (equivalent to a total of one atomic layer of Mn ions) we deposit a 13.5nm (50 monolayer) $Ga_{0.76}Al_{0.24}As$ barrier layer, which is either doped with Be or undoped. The free holes introduced by Be acceptors in the GaAlAs barrier then “flow up” into the GaMnAs layer, much like air bubbles in a liquid. This process is referred to as modulation doping. Eventually, the local Mn ions and the free holes in the system form one “global” complex via strong anti-ferromagnetic (AF) coupling.

We performed ferromagnetic resonance (FMR) measurements on a series of such GaMnAs/GaAlAs heterostructures modulation-doped by Be, to study magnetic moment and anisotropy of the Mn-ion/hole complex described above. In FMR experiment, the total magnetic moment of the complex precesses (much like a top) around the direction of the static magnetic fields present in the system (i.e., the applied magnetic field and the anisotropy magnetic field) at the Larmor frequency ω. When microwaves are present, absorption occurs when the microwave frequency coincides with the precession frequency. The FMR experiments provide a direct measure of magnetic anisotropy fields (which are described by two components: cubic and uniaxial) and of their dependence on the free carrier concentration. We find that an increase in doping – in addition to raising the Curie temperature of the GaMnAs layers – unambiguously increases the value of the uniaxial anisotropy field, and reduces the cubic anisotropy field. In addition, the shift of the resonance condition (i.e., the Larmor frequency ω referred to above) is also affected by the free carriers, automatically providing a measure of the contribution of free holes to the magnetization. To our knowledge this is the only measurement which gives this information. This work has been submitted to Physical Review B, Rapid Communication. [X. Liu *et al.*, cond-mat/0407371]

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V. Metlushko, *Univ. of Illinois, Chicago*, Albert Chang, *Duke*

EDUCATION & OUTREACH

- Graduate student Shaoping Shen is doing the ferromagnetic resonance experiment with Bruker EPR system; graduate student Weng-Lee Lim (back) is doing the magneto-transport experiment on a series of ferromagnetic/nonmagnetic hybrid-semiconductors samples.

- International visitor exchange at levels, from undergraduate student to associate professor, from six different nations on three different continents. **[see participants and image at http://www.nd.edu/~condmat/]**